An Electronically Steerable Flash Lidar (ESFL)

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Current space-based lidar systems for Earth remote sensing have a number of inherent limitations that impact their use for broader science applications. These include no cross-track coverage, fixed spatial sampling that forces pointing control to be performed by the spacecraft, cloud loss over many types of scenes, and in general, lifetimes set in part by the number of laser shots fired. The Electronically Steerable Flash Lidar (ESFL) is a new concept developed to help in overcoming these limitations. It combines a new "Flash" focal plane technology that allows both imaging and waveform ranging, with a multi-beam steering capability. Steering is achieved via an acousto-optic beam deflector that splits the laser into multiple beams that can be independently accessed and pointed without the need of mechanical scanners or boresight mechanisms. A full demonstration unit of ESFL was completed and successfully tested both in laboratory and aircraft flight tests, as presented at the 2010 ESTF conference. Three weeks of testing on aircraft have now been completed, the data processed to Level 1b, and science analysis of the data for multiple types of forests is being completed. This includes inter-comparison with commercial scanning lidar data. Ground validation work in a prescribed burn region is also being completed. Modeling of the improvement in spatial sampling from a potential orbital version of the instrument was completed and shows a twofold improvement in forest height accuracy of current approaches, and a threefold improvement in collection time. The significant improvement by using cloud avoidance algorithms to point the beams for improving global coverage as a function of region and season has also been analyzed using MODIS data. The instrument was accepted into the NASA Airborne Instrument Technology Transition program, and its performance and reliability are being improved so that it can be used by scientists for broader studies.

Flash focal plane arrays (FFPA) are an example of new "smart pixel" CMOS-based cameras. Used with a pulsed laser they can both image the laser intensity as well as create a range (or distance) image; a 3-D camera. Generally, each pixel has in its read-out integrated circuit (ROIC) unit cell amplifiers, timing networks, and associated support circuitry that enables it as an imaging lidar. This can include photon counting networks. A wide range of optical photodiode arrays have been developed to match these ROICs; including different polarity p/n and avalanche photodiodes (both linear and Geiger mode). These have been developed in the standard materials; for example, silicon, InGaAs, and HgCdTe, and are undergoing rapid development in terms of sensitivity, noise and wavelength operating range. ESFL utilizes a commercial flash focal plane array made by Advanced Scientific Concepts (ASC) which has a 128 by 128 pixel focal plane array that utilizes custom InGaAs linear-mode avalanche photodiodes. The ROIC utilizes a timing network that has a clock frequency that can be varied between 100 and 300 MHz, and the ability to save 44 range time bins for each pixel, thus creating a full lidar waveform. The first FFPA built "bottoms up" to meet NASA's stringent parts and system reliability requirements has now been completed, with the first unit integrated into the NASA/Ball STORRM lidar integrated onto Endeavour for its last flight to the ISS, for testing as part of a rendezvous and docking sensor.

Flash lidars with their "staring" arrays open up a number of new system design solutions. Using pulsed lasers to "illuminate" and range to a scene can be seen as a modern version of the old instamatic with a flashbulb – modern 3-D digital photography. As with a flashbulb, the efficient use of the light is critical to the camera's performance. But lasers have the advantage in that they can be collimated into beams. While flash focal plane arrays are currently available at 256 by 256 pixels (or 0.066 Mpixels), the core technology is common with standard digital cameras so we can anticipate larger sizes becoming available. However, a critical metric for performance is ultimately the amount of laser light that can be collected and imaged onto the flash focal plane – photons/pixel. For many cases, especially ones with limited available electrical power application such as satellites, it would be advantageous to use the beam properties of the laser to concentrate the light, trading off the number of pixels used in an image with the range (distance) over which the image is created. For the STORRM lidar, a two setting diverging optic is used with the laser, allowing this range versus pixel number optimization to be made as the range to the target changes.

For applications involving topographic mapping of the Earth's surface from aircraft or spacecraft, one natural solution is to form the laser into a fixed "pushbroom" beam that illuminates one (or a few) pixels along track while collecting a broad cross-track swath. For example, Ball Aerospace's Topographic Mapping Flash Lidar (TMFL) uses a holographic beam diffuser to shape the laser into a line whose image is 128 pixels wide (crosstrack) and 1 pixel along track. The use of a microlens array integrated onto its InGaAs avalanche photodiode array provides >90% fill factor enabling this approach. Flight testing of TMFL in 2010 showed how this approach could be used to map topography and forests, but also water surfaces for wind estimates and even plume dimensions including multiple scattering effects.[1]

The Electronically Steerable Flash Lidar (ESFL) takes a different approach to efficiently using laser light with the flash focal plane arrays. Instead of a fixed beam pattern, ESFL uses adaptable beam control to deterministically control the number of beams and their direction – putting the laser light where the measurement is to be made. While there are a number of technologies that can point and shape laser beams, a single-axis acousto-optic beam deflector unit is used that allows the laser light to be efficiently deflected into a number (up to ten for this configuration) of separate beams. The divergence of the beams (and therefore the ground footprint size) in this configuration is set in the lab prior to the flight. A unique aspect of using a Flash lidar is that the beam can be imaged by multiple pixels simultaneously. For the demonstration unit, typically 4.5 meter diameter beam footprints were used and these were imaged onto approximately 120 pixels (a 12 pixel diameter image). The configuration (number of beams and pointing of each) can be changed for every pulse of the laser, running at a 30 Hz repetition rate. Where to point the beams and how many is set by the system beam controller, which uses a number of secondary inputs. The operator can order a fixed number of beams fully covering the cross-track direction – a pseudo-pushbroom. An alternating pattern or scanned mode can also be pre-defined. A "geolocation mode" uses input from a GPS/IMU unit integrated to the lidar to point the beams to track specific transects defined by their GPS coordinates. In this mode, the orientation of the aircraft is corrected for, ensuring beam alignment to the desired transect. A "cloud avoidance" mode uses input from a co-boresighted color camera with an algorithm that uses a simple "brightness" algorithm to identify clouds in the scene and to point the beams between the clouds to avoid cloud loss.

The program was set up to design, test, and calibrate the lidar instrument implementing the new technologies. To prove that the new lidar design would meet the overall objective of being able to characterize forest canopies, a field campaign was carried out. In 2009 and 2010 three weeks of aircraft flight testing were completed on a Twin Otter aircraft over a variety of forest types that were chosen based on their being representative of important ecological types, as well as having been previously studied.[Table 1] Two methods of "validation" were used, the first was that collocated commercial scanning lidar data was collected at all of the forest sites, the second was ground validation – data analysis of both methods is still in process. The commercial scanning lidar data was collected with the Leica ALS 50 system, one of the common lidars used currently in airborne data collections over forests.

TABLE 1.
SUMMARY OF THE FLIGHT TESTING THAT WAS DONE ON THE ESFL GRANT TO HELP PROVE OUT ITS CAPABILITY FOR FOREST SCIENCE.

Flight Location	Forest Foliage Coverage	Type of Forest
Manitou Experimental Forest (MEF) , CO	~70%	Ponderosa Pine canopy, juniper shrubs
Stephen F Austin Experimental Forest (SFAEF) , TX	>95%	Upland - Loblolly, shortleaf pine, oak, Pecan, Elm, Red Maple Floodplain- sweetgum, various oaks, blue beech, black gum
Smithsonian Environmental Research Center (SERC) , MD	>95%	Dominant Tulip poplar, sweet gum Secondary - red maple, white oak, American beech, red/black oaks

To perform this comparison, careful work was required to obtain overlapping and well geo-located data. Three test criteria were chosen for comparison at Colorado State University, the ground height under canopy, the forest height, and the canopy penetration. While ESFL is a full waveform lidar (see Fig. 1), the Leica is a four return system, so four ranges per laser pulse were measured. Data analysis showed that the two lidars are well-correlated (≥ 84%) at the Manitou and SFAEF sites for ground and forest height. The ground elevations agreed to better than the range bin size of ESFL (0.75 m). Canopy heights agreed between the lidars to < 3.5 m rms, and ESFL shows higher canopy penetration (by > 70%) at SFAEF where there is more understory and underbrush. A publication on the results is in process. This cross-comparison approach showed that the two types of lidars agree at a fundamental level. This opens the way to exploring how the lidar imaging capability of ESFL can next be exploited for greater science return. The SERC site data comparison with the commercial lidar and potentially other NASA lidars is still being performed.

Ground validation work has been performed at a number of prescribed forest burnsites in Colorado as part of a larger study to understand the role of forest fire on atmospheric carbon exchange, regional carbon budgets, and soil respiration. Intercomparison of the lidar data and ground data are in process at the University of Wyoming.

A third part of the program, in addition to the technology demonstration and science evaluation, was a study of the improvements in Earth remote sensing if the ESFL concept was

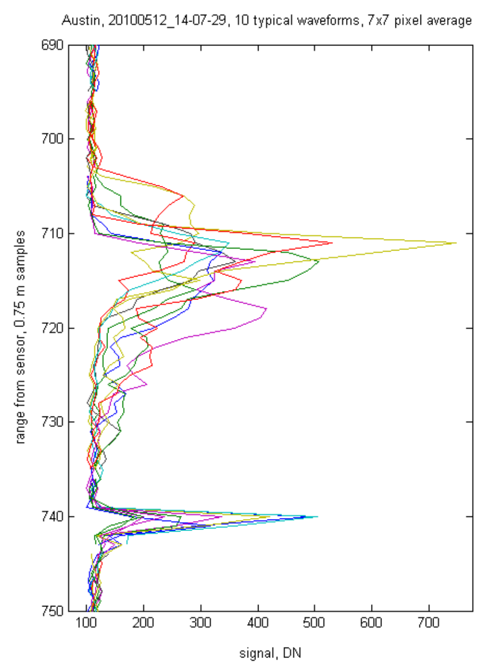

Fig. 1 Raw lidar waveforms taken at the Stephen F. Austin Forest taken from aircraft. The vertical scale is in range from the aircraft in bin number (0.75 m per bin) and the x-axis is signal strength. Each waveform is from a single laser pulse. One of the eight laser footprints has been imaged, and the center 7 by 7 pixel sub-image is averaged. The canopy signal occurs in range bins 710- 730 and the ground appears near range 740. A laser footprint is 4.5 m and a pixel footprint is 0.35 m for this data.

implemented in space. To motivate the studies a notional space-based instrument design was created based loosely on the CALIPSO design. [2] This assumed a 1 meter diameter telescope with a 1 degree field of view in a 400 km orbit. A 750 mJ, 40 Hz laser at 1064 nm was assumed. This is a class of laser developed at Fibertek for other NASA missions and at TRL levels needed for a space program. A flash focal plane with similar performance as to what was used on the aircraft instrument was assumed, with the understanding that this would have to be re-designed for a space implementation. A radiometric model for signal-to-noise was then constructed assuming different forest canopy coverage. A difficulty is that there is no commonly accepted requirement for what signal-to-noise is required for sampling different forest types with full waveform lidars. The model gave that for 98% forest cover the ground could be detected with up to 36 individual beams (assuming a cloud free atmosphere). More beams (of lower energy) can be used by ESFL when the forest cover is less dense, improving the overall spatial sampling. The impact on space-based measurements of forest biomass of having this number of beams spread cross-track was modeled at Colorado State University. [3] The ESFL "hybrid" approach was found to offer two substantial improvements as compared to the sampling approach that was planned for the DESDynI lidar. The larger and denser cross track coverage allowed the mission to be completed in one third of the time, while achieving simultaneously a higher precision in measuring the maximum forest canopy height by a factor of up to two because of a better understanding of the local topography. The ESFL concept trades the contiguous along track coverage of DESDynI for much higher cross track coverage.

As was stated throughout the NRC Decadal Survey for Earth Science, interference and loss of data because of clouds is a significant problem for space-based lidars trying to measure near or at the Earth's surface. ESFL was designed to address the issue. The "Cloud Avoidance" mode, as demonstrated in the lab and discussed at ESTF 2010, [4] provides a means to steer beams around broken clouds in order to be able to make measurements near the surface. To evaluate how effective this might be, a study was performed at LaRC using MODIS data. The MODIS 1 km cross track pixels were aggregated into groups of five (5 km cross track) and the cloud mask values of 3 or 4 were used to indicate "cloud free". For each group a clearness percentage was recorded, as well as the Nadir status. Daily and monthly averages were taken, across nine landmass regions. The improvement in coverage varied with season and sub-region. Fig. 2 illustrates one result for South America indicating an improvement of up to 50% across parts of the Amazon for the month of June. Similar studies were carried out using 10 km cross track swaths as well as 5 and 10 km square grids, with similar types of improvements; the results will be published. There are many caveats in interpreting these results, including that typical lidar footprints will be < 100 m. While more work would need to be done to evaluate the improvement for an actual mission, the results remain significant. They illustrate that the ESFL system design offers another significant improvement in mission-level efficiency by utilizing adaptive beam –steering for cloud avoidance. Combining the improved cross-track coverage and the cloud avoidance – both adapting to the forest and cloud scene below- should offer higher science return within a much shorter mission life- improving overall mission reliability.

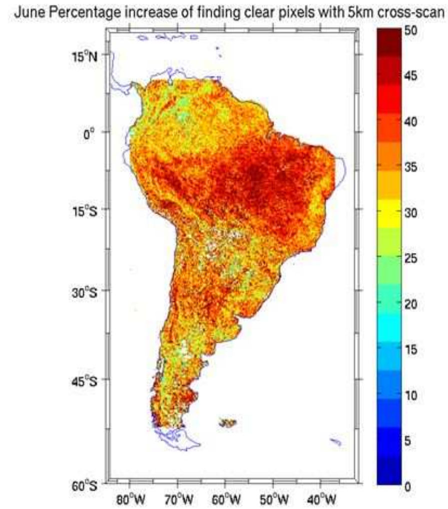

Fig. 2 Analysis using MODIS data of the improvement in ground coverage that could be achieved by the use of an electronically steerable flash lidar utilizing adaptive cloud avoidance algorithms which direct the beams between clouds.

ESFL was awarded a NASA Airborne Instrument Technology Transition grant from NASA to mature its design and advance its capability so that it could become a "facility" instrument – available to scientists for airborne science campaigns. Upgrades to the hardware are being completed in the first year. These will enable ESFL to fly at higher altitudes to enable 25 m beam footprints to match those of the DESDynI lidar to support ground comparisons. Other upgrades include increasing the data throughput and storage to enable longer swaths to be collected. In the second year software upgrades will increase autonomy and enable new adaptive capability for the system.

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